

OBLIQUE IMPACTS: CATASTROPHIC VS. PROTRACTED EFFECTS; P.H. Schultz, Dept. Geological Sciences, Brown University, Providence, RI 02912 and D.E. Gault, Murphys Center of Planetology, Murphys, CA 95251.

Proposed impacts as the cause of biologic catastrophes at the end of the Cretaceous (1) and Eocene (2) face several enigmas: protracted extinctions, even prior to the stratigraphic cosmogenic signature; widespread but non-uniform dispersal of the meteoritic component; absence of a crater of sufficient size; and evidence for massive intensive fires. Various hypotheses provide reasonable mechanisms for mass mortalities: global cooling by continental impact sites; global warming by oceanic impact sites; contrasting effects of asteroidal, cometary, and even multiple impacts; and stress on an already fragile global environment. Yet not every known large impact is associated with a major biologic catastrophe. We expand on an alternative: the consequences of an oblique impact (3). The most probable angle of impact is 45° with the probability for an impact at smaller angles decreasing as $\sin 2\theta$ (4): A vertical impact is as rare as a tangential impact with a 5° impact angle or less occurring only 8% of the time. Consequently a low-angle impact is a rare but probable event. Laboratory experiments at the NASA-Ames Vertical Gun Range reveal important information about cratering efficiency, impact vaporization, projectile dispersal, and phenomenology, thereby providing perspective for possible consequences of such an impact on both the Earth and Moon.

Energy Partitioning: Cratering efficiency decreases as $\sin\theta$ for particulate gravity-controlled and $\sin^2\theta$ for strength-controlled targets (4). This decrease reflects the fraction of energy carried away by the ricocheted projectile and concomitant ejecta as shown in Fig. 1 (4, 5). Comparison of the momentum partitioned to the target and to a downrange ballistic pendulum reveals that the ricocheted projectile alone comprises 80–90% of the lost energy fraction with velocities close to the original impact velocity. Laboratory impacts at 6 km/s are far from the 12–75 km/s characterizing terrestrial impacts, thereby failing to include the effects of melting and vaporization. Use of easily devolatilized/vaporized targets (dry-ice, water, carbonates), however, permit exploring such effects (6, 7). The fraction of energy partitioned to vaporization increased with velocity but approached a constant 50% for velocities exceeding 4 km/s at an impact angle of 15° . Since the ricochet debris carries away about 30% of the initial impactor energy, only 20% is left for crater formation. While the total energy in the vapor cloud remains nearly constant, the total vaporized mass increases with the square of the impact velocity. For a given velocity, the vaporized mass fraction appears to increase dramatically: ten-fold from impact angles of 90° (vertical) to 15° (Fig. 2).

Vapor-Cloud Evolution: High frame-rate photography (35,000 fps) reveals that low-angle impacts produce both a high-velocity downrange gas cloud with entrained ricochet debris and a cloud that expands hemispherically above the impact point. The downrange cloud was observed to expand, singe, and scour the surface. The presence of an atmosphere, however, can significantly restrict the expansion of the downrange cloud at laboratory scales. Gas expansion from low-angle impacts is largely uncontained by the developing crater cavity, and the expansion velocity rapidly approaches theoretical predictions (see 7). Expansion from near-vertical impacts is partly contained within the cavity, thereby forming a jet.

Implications: A major oblique impact on the Earth can have five effects: First, the significant decrease in cratering efficiency results in a smaller crater than expected for a given impactor energy. Consequently, direct evidence for such an event may have been destroyed or would be associated with an insignificant crater. Second, an impact at 15° generates ten times as much vaporized mass as a vertical impact. As a result, a 2 km-diameter object impacting a deep ocean would inject as much as 10^{17} g of H_2O into the atmosphere; an impact into carbonate-rich sediments could release several times the present atmospheric inventory of CO_2 . Third, the coupling between the thermal energy of the vaporized mass and the pre-existing atmosphere is much more efficient at low impact angles. Fourth, the downrange hot vapor cloud is capable of incinerating a broad swath extending up to 1000 km downrange. Such a fireline may be much more effective and longer lived than a thermalized annulus quickly buried by ejecta in a near-vertical impact. And fifth, the ricocheted projectile would be widely and efficiently dispersed. Possible consequences of this last observation include placing impactor/impacted debris into terrestrial orbit, the effects of which are discussed below.

An oblique impact on the Moon also could affect the Earth. In this case, a significant widespread cosmogenic signature might occur in the terrestrial record even without the formation of a crater. Calculations of ejecta trajectories from lunar impacts reveal that a small but measurable quantity of debris from the Moon should be accreted on the Earth (8). If reapplied to ricochet from an oblique impact, then preliminary results indicate that a 20° -wide band impact zone on the Moon would allow

the ricochet debris to re-impact the Earth. Although rarer (a 1 km-diameter impactor every 200 my), the possibility exists and needs further study.

Terrestrial Debris Ring: A significant fraction of the ricochet component can achieve geocentric orbit because it retains an appreciable fraction of the initial impactor velocity and because of gas-dynamic forces within the accompanying vapor cloud. For relatively small impacts (Impactor diameters less than 5 km), such an event would produce staged or even multiple deposition of the cosmogenic (Ir) and impact signatures (microtektites) over the brief (1000 yr) orbital lifetime. The North American tektite and microtektite strewn field contains about 10^{15} g (9), about 1% of the mass of a 4 km-diameter impactor. The stratigraphic record indicates that clinopyroxene-bearing spherules accompanied an Iridium anomaly and an extinction event 34 my but predated by about 10,000–20,000 years deposition of the North American tektite and microtektites (9). For very large impacts (>20 km), however, orbital injection of just 10% of the combined ricochet, ejecta, and vapor cloud mass would exceed 10^{18} g. Ablation products from re-entry of this debris as the orbits decayed might affect upper atmospheric conditions over a time longer than commonly indicated for ejecta directly injected into the atmosphere immediately after impact. For sufficiently large quantities of orbiting debris, however, dynamical models indicate that collisional damping would rapidly (1–100 yrs) produce a Saturn-like ring (10) having potentially more severe long-term consequences for the solar flux at the Earth's surface. Oblique Impact by a 20 km-diameter object appears to be sufficient to produce enough ricochet/ejecta debris. The origin for such a ring is significantly different from that proposed by O'Keefe (11).

Concluding Remarks: Oblique impacts are rare but certain events through geologic time: A 5° impact by a 2 km-diameter impactor on the Earth would occur only once in about 18 my with a 10 km-diameter once in about 450 my. Major life extinctions beginning prior to the stratigraphic cosmogenic signature or protracted extinctions seemingly too long after the proposed event may not be evidence against an impact as a cause but evidence for a more complex but probable sequence of events.

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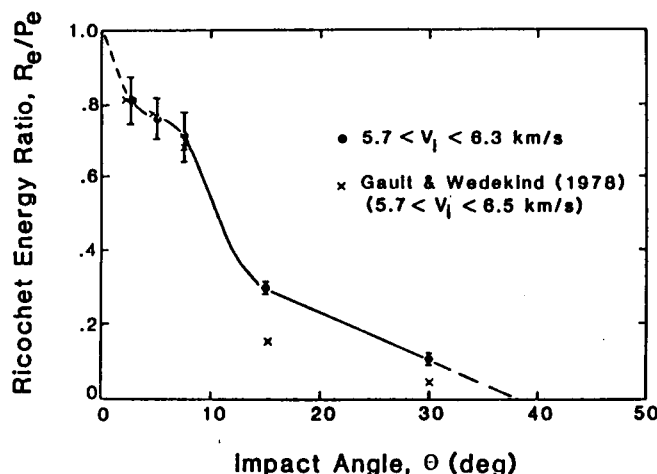


Figure 1. Variation of ricochet energy (R_e) relative to initial projectile energy (P_e) as a function of impact angle.

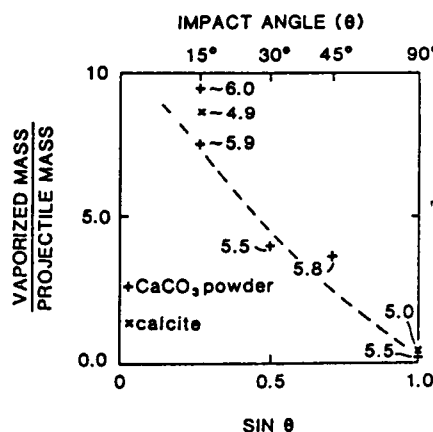


Figure 2. Vaporized mass relative to projectile mass as a function of impact angle for different impact angles.